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Distortion Control through Synchronized Vacuum Heat Treatment

Verzugsarme Vakuumwärmebehandlung im Takt der Fertigung

Abstract/Kurzfassung

Controlling distortion is of key importance during the case hardening process for the production of automotive and non-automotive metallic components. By effective control of distortion and the variation of distortion, significant costs in post heat treatment machining processes can be avoided. In some cases it is even possible to eliminate all post-machining. In other cases it may be possible to avoid the press-quenching of individual components, resulting in huge cost-benefits. A recently introduced new vacuum furnace design allows the treatment of small batches in a single layer of parts ("2D-treatment") which allows for easy automated loading and unloading of the fixture-trays. By using the small batch concept, a continuous flow of parts can be established ("One Piece Flow"). There is no need to wait until enough parts are collected to build a large batch with multiple layers ("3D-batch"). This compact furnace unit can be implemented into the heart of the production chain and provides heat-treatment processes which can be fully synchronized with the green and hard machining-operations. When performing case hardening, the components are Low Pressure Carburized (LPC) at high temperatures (1050 °C) followed by gas quenching. The treatment in single layers offers an optimum in quality regarding: temperature homogeneity, quench homogeneity and distortion control. Typical components for this technology come from the automotive, aerospace and tool industry. The directly following contribution in this Journal (A. Schüler et al., p. 90-98) shows more results achieved with this technology on selected truck-components such as gears and sliding-sleeves. ■

Keywords: Distortion, gears, case hardening, Low Pressure Carburizing, High pressure gas quenching, One Piece Flow production

Die Reduzierung der Wärmebehandlungsverzüge ist von größter Bedeutung bei der Einsatzhärtung von metallischen Komponenten. Durch Minimierung der Maß- und Formänderungen und insbesondere deren Streuungen können die Kosten für die Hartbearbeitung der Bauteile enorm gesenkt werden. In einzelnen Fällen kann die Hartbearbeitung sogar komplett entfallen. Zudem kann in weiteren Anwendungsfällen das Presshärten der Bauteile eliminiert werden, was ebenfalls zu enormen Kostenreduzierungen führt. Ein kürzlich eingeführtes neues Vakuum-Wärmebehandlungssystem ermöglicht die Behandlung von kleinen einlagigen Chargen („2D-Chargierung"). Durch die Nutzung dieser kleinen Chargen wird ein kontinuierlicher Bauteilfluss gewährleistet („One Piece Flow"). Zudem ermöglicht die einlagige Behandlung ein einfaches automatisiertes Be- und Entladen des Chargen-Werkstückträgers. Es ist nicht mehr notwendig, die Bauteile zu sammeln, bis genügend Bauteile für eine große mehrlagige Charge („3D-Chargierung") vorhanden sind. Dieses neue kompakte Ofensystem kann in das Herz der Fertigung integriert werden und ermöglicht Wärmebehandlungsprozesse, die voll mit der Grün- und Hartbearbeitung synchronisiert sind. Die Bauteile werden dabei mittels Niederdruckaufkohlung (Low Pressure Carburizing, LPC) bei hohen Temperaturen (1050 °C) aufgekohlt und dann mittels Hochdruckgasabschreckung abgeschreckt. Die einlagige Behandlung bietet dabei signifikante Vorteile im Hinblick auf: Temperaturgleichmäßigkeit, Gleichmäßigkeit der Abschreckung sowie Reduzierung der Maß- und Formänderungen. Typische Einsatzgebiete für diese Technologie kommen aus dem Bereich der Automobil-, Luftfahrt- und Werkzeugindustrie. In dem nachfolgenden Beitrag dieser Zeitschrift (A. Schüler et al., S. 90-98) werden weitere Ergebnisse gezeigt, die mit dieser Technologie an ausgewählten Nutzkraftfahrzeug-Bauteilen wie Getrieberäder und Schiebemuffen erzielt wurden. ■

Schlüsselwörter: Verzug, Maß- und Formänderungen, Zahnräder, Wellen, Einsatzhärtung, Niederdruckaufkohlung, Hochdruckgasabschreckung, One Piece Flow

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1 Introduction

Proper distortion control has become even more important than in previous days. Distorted gear components cause noise in the transmission and may even create problems during transmission assembly. Distortion has a strong cost-impact, because distorted components often need to be hard-machined after heat treatment. Better control of distortion means:

- less cycle time per part in hard-machining,
- less hard-machining capacity needed and
- less tooling cost for hard-machining.

With an excellent control of distortion for some applications hard machining can be completely eliminated. For other applications it may be possible to avoid the press-quenching of individual components, resulting in huge cost-benefits.

2 High pressure gas quenching

The relevant mechanisms that cause distortion of components during heat treatment have been described extensively in literature [1, 2]. *Walton* [3] published the numerous potential factors that are influencing distortion.

By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ) heat treat distortion can be significantly reduced. LPC is a case hardening process which is performed in a pressure of only a few millibar using acetylene as the carbon source in most cases [4]. During HPGQ the load is quenched using an inert gas-stream instead of a liquid quenching media. Usually nitrogen or helium are used as quench gas [5–7].

HPGQ offers a tremendous potential to reduce heat treat distortion. Conventional quenching-technologies such as oil- or polymer-quenching exhibit inhomogeneous cooling conditions. Three different mechanisms occur during conventional liquid quenching: film-boiling, bubble-boiling and convection. Resulting from these three mechanisms the distribution of the local heat transfer coefficients on the surface of the component are very inhomogeneous. These inhomogeneous cooling conditions cause tremendous thermal and transformation stresses in the component and subsequently distortion. During HPGQ only convection takes place which results in much more homogenous cooling-conditions [8].

Significant reductions of distortion by substituting Oil-quench with HPGQ have been published [9]. Another advantage of HPGQ is the possibility to adjust the quench-intensity exactly to the needed severity by choosing quench-pressure and quench-velocity. Typical quench pressures range from 1 bar to 20 bar. The gas-velocity is controlled by a frequency converter. Typical gas-velocities range from 0.5 m/s to 20 m/s depending on the part-geometry and the steel-grade of the component.

As of today, the process of LPC and HPGQ is typically performed in batches consisting of several layers of production parts, so called "3D-batches".

3 2D-heat treatment

To further reduce distortion, a new vacuum furnace design was introduced which allows the single layer treatment ("2D-batches") of parts. In comparison to treatment of big batches in multiple layers, the single layer treatment using LPC and HPGQ provides

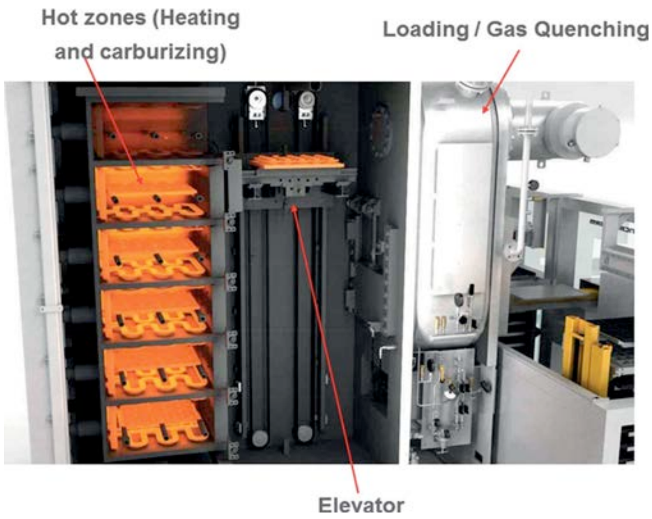

Fig. 1. SyncroTherm® – schematic view into the system

Bild 1. Schematische Darstellung der SyncroTherm®-Anlage

- homogenous and rapid heating of the components
- homogenous and precisely controlled gas quenching.

All the variations in a 3D-batch from layer to layer are eliminated, which allows further reduction in distortion-variation within the load. Figure 1 shows the new heat treatment system for treatment of 2D-batches which was developed by ALD Vacuum Technologies (Patent pending).

The treatment cycle in this new unit is described in the following. A single tray with untreated "green" parts enters the system through the outer door of the quench cell. After evacuating, the tray is then brought with an elevator through the housing into one of the "hot zones". A hot zone is a single slot that can hold one tray of parts. There are 6 hot zones vertically arranged inside the housing. The pressure in all hot zones is identical, but each hot zone has its own temperature control and its own supply of process-gases. Once the tray has entered a hot zone, it is being heated up rapidly from all sides and then carburized at 1050 °C using acetylene. After the carburizing is completed, the tray is brought with the elevator back to the quench cell. After closing the door between quench cell and housing, the quench cell is flooded with nitrogen which circulates through the cell. A heat exchanger inside the quench cell is used to cool the circulating gas. The system works with a maximum gas pressure of 10 bar nitrogen. But to keep running costs low, it is recommended to quench with max. 6 bar nitrogen. Once the quenching is completed, the quench cell is vented with air. Then the parts are removed from the heat treat unit and they enter the tempering unit.

Besides the benefits regarding homogeneity of treatment and improved distortion control, the system allows to establish a new production philosophy. Today's production philosophy for gear components usually relies on the traditional separation between soft machining, heat treatment and hard machining. Heat treatment is performed in a central hardening shop. There is no continuous flow of production-parts between the different operations such as soft machining, heat treatment, shot-peening and hard machining. Instead the parts are collected into batches and then moved from operation to operation. So large numbers of production-parts are stored in buffers or are in transit between the different operations.

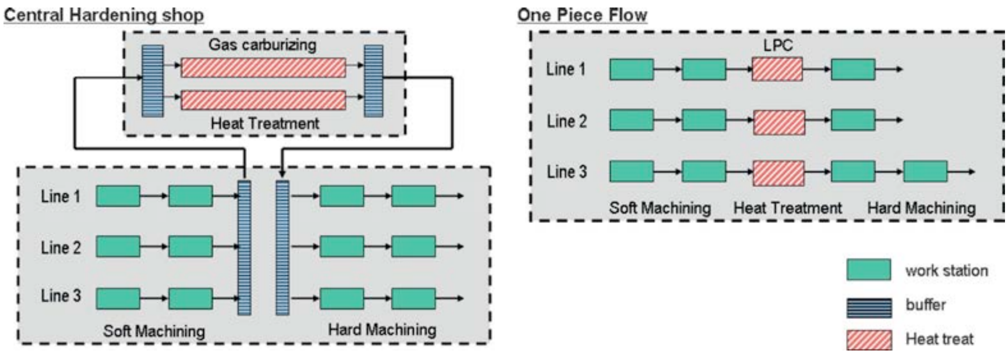

Fig. 2. Gear manufacturing with central hardening shop and with "One Piece Flow" integrated manufacturing lines

Bild 2. Getriebefertigung mit dem Konzept „Zentralhärterei" und mit dem Konzept „One Piece Flow - Fertigung"

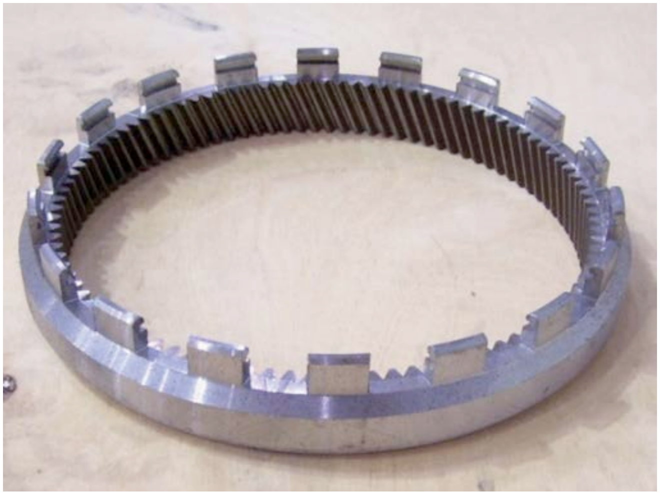

Fig. 3. Reaction Internal gear (d = 152 mm, 103 internal teeth)

Bild 3. Innenverzahntes Hohlrad (d = 152 mm, 103 Zähne)

In order to establish a more effective and economic production of gear components, the goal is to move away from batch type logistics and move towards a "One Piece Flow" of production, see Figure 2. The goal is to move single parts from operation to operation instead of moving batches of parts. This One Piece Flow production system (OPF) would realize a continuous flow of production parts and would avoid huge efforts for storage and transportation of parts between operations [10, 11]. If such a total integration of all operations can be established, then this will offer new possibilities for automation, which again leads to a reduction of costs. Additionally a higher level of automation will result in a reduction of defects in quality such as handling damage.

The above described new heat treatment module allows for total integration into the manufacturing line creating a synchronized production flow with gear machining.

Following the philosophy of „One Piece Flow" the parts are
- taken one by one from the soft machining unit,
- heat treated in time with the cycle time of soft machining and then
- passed down one by one to the hard machining unit.

Although the parts are not treated individually but treated in trays, the parts are individually loaded to the heat treat unit and individually unloaded from it. So the continuous flow of single parts is established.

The concept and the technology of "One Piece Flow" heat treatment have been published earlier in more detail by the authors [12].

4 Distortion studies

4.1 Reaction internal gears

A distortion study was initiated to quantify the improvement in distortion-control when switching from multiple-layer to single-layer treatment. A reaction internal gear from a six speed automatic transmission was chosen as test-component. The reaction internal gear has an outer diameter of 152 mm, 103 internal teeth and is made of 5130 material, see Figure 3. The case hardening depth CHD after heat treat is specified as 0.3…0.6 mm and surface hardness is specified as 79…83 HRA.

The tests with multiple layer treatment were performed in a ModulTherm-system, while the tests with single layer treatment were performed in a SyncroTherm-system (see Figure 1). Table 1 shows the different test-conditions.

As of today the serial production of these internal gears takes place in ModulTherm-systems with multiple-layer treatment. To analyse the distortion data from the ModulTherm-system, a random load from current standard production process was used and complete load-sizes were treated [13]. 48 pre-measured parts were equally distributed into different layers of the load, see Figure 4. Additionally to cover all "extreme" positions in the load, it was

System	Carburizing temp.	Quench gas	Number of layers	Parts per load	Cycle time
ModulTherm	900 °C	He Dynamic quench*	10	120	135 min
SyncroTherm	900 °C	N2	1	1	135 min
SyncroTherm	1050 °C	N2	1	1	24 min

*Parts were quenched with an optimized "dynamic quenching" process as described earlier [13].

Table 1. Test conditions for the distortion study on reaction internal gears

Tabelle 1. Prozessparameter für die Verzugsstudie mit innenverzahnten Hohlrädern

Fig. 4. Multiple layer (left) and single layer (right) – batch of internal ring gears (CFC fixturing)

Bild 4. Dreidimensionale (links) und zweidimensionale Chargierung (rechts) von innenverzahnten Hohlrädern (auf CFC-Chargenträgern)

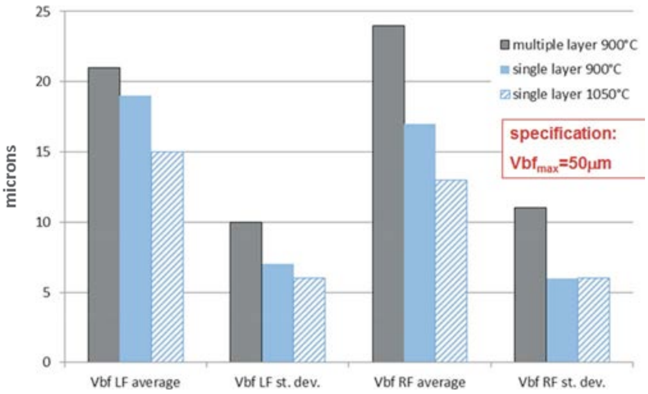

Fig. 5. Helix angle variation Vbf after heat treatment; comparison between multiple layer treatment (ModulTherm) at 900 °C and single layer treatment (SyncroTherm) at 900 °C and 1050 °C (LF = left flank; RF = right flank; st. dev. = standard deviation)

Bild 5. Streuung der Flankenlinienwinkelabweichung Vbf nach der Wärmebehandlung; Vergleich zwischen dreidimensionaler (ModulTherm) bei 900 °C und zweidimensionaler Chargierung (SyncroTherm) bei 900 °C und 1050 °C (LF = linke Flanke; RF = rechte Flanke; st. dev. = Standardabweichung)

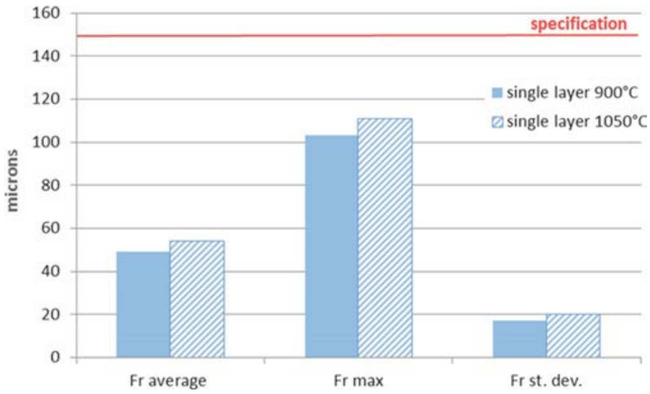

Fig. 6. Circularity Fr after heat treatment; comparison between single layer treatment at 900 °C and 1050 °C (SyncroTherm)

Bild 6. Rundheit Fr nach der Wärmebehandlung; der Vergleich zeigt Werte mit zweidimensionaler Chargierung bei 900 °C und 1050 °C (SyncroTherm)

made sure that parts from all 8 corners and parts from the middle of the load were geometrically inspected.

In the SyncroTherm-system, for both carburizing temperatures four tests were performed with single-layer treatment with eight parts placed each time on the tray, see Figure 4. All fixturing was made of carbon reinforced carbon (CFC) material. Before the distortion-data was collected, it was made sure that the metallurgical quality in terms of hardness profile, microstructure and core hardness was identical for all three populations of parts.

All measurements were performed with a CNC analytical gear-checker. Four teeth were inspected for each gear and both left flank and right flank were examined per tooth.

Figure 5 shows a comparison of the helix angle variation (Vbf) measured for the multiple-layer treatment (ModulTherm) and for the single-layer treatments (SyncroTherm). The average and the standard deviation of helix angle variation (Vbf) after heat treatment is given for both flanks. The already low values of Vbf from multiple-layer treatment were further reduced when applying single layer treatment.

While the average variation of the left flank was only slightly reduced, the standard deviation was reduced by 30 % down to seven microns when switching from multiple to single layer treatment with carburizing at 900 °C. For the right flank the average of Vbf was reduced by 30 % and the standard deviation of Vbf was reduced by 45 % when treating at 900 °C. The lower amount of helix angle variation of the parts from single-layer treatment indicates, that they are flatter after heat treatment compared to the ones from multiple-layer treatment.

When comparing the single layer treatment at 900 °C with 1050 °C, no increase in Vbf was observed. This is certainly remarkable. A standard 5130 steel grade without microalloying for grainsize control was used for all tests. Although significant grain growth was detected after treatment at 1050 °C, this did not lead to increased distortion.

The circularity of the internal ring gears was studied as well. Figure 6 shows the circularity Fr after heat treatment comparing carburizing at 900 °C and 1050 °C both with single-layer treatment. For both temperatures the values are within specification and no significant increase was observed when raising the treatment temperature up to 1050 °C.

4.2 Input shafts

The distortion of input shafts treated in the new SyncroTherm-unit was analysed as well, see Figure 7. The Input shaft is made of 16MnCr5 material, has a mass of ca. 0.7 kg and is treated with a load-size of 30 shafts per tray. The case hardening depth CHD after

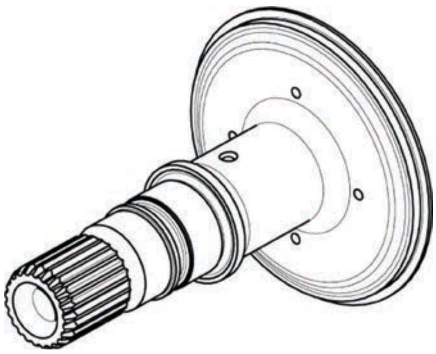

Fig. 7. Input shaft made of 16MnCr5 (ca. 0.7 kg per shaft)

Bild 7. Eingangswelle aus 16MnCr5 (ca. 0,7 kg pro Welle)

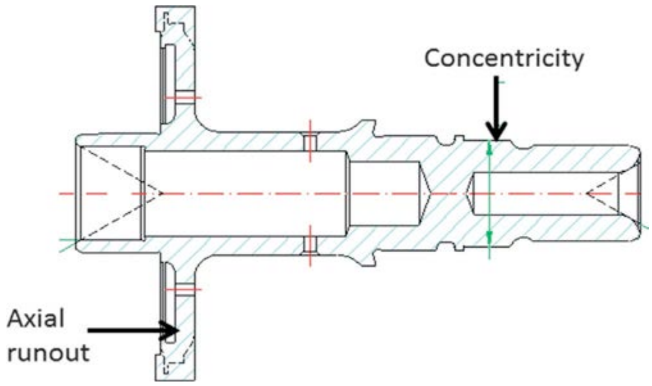

Fig. 8. Positions for measurement of axial runout and concentricity on the input shaft

Bild 8. Messpositionen für Planlauf (axial runout) und Rundlauf (concentricity) der Eingangswelle

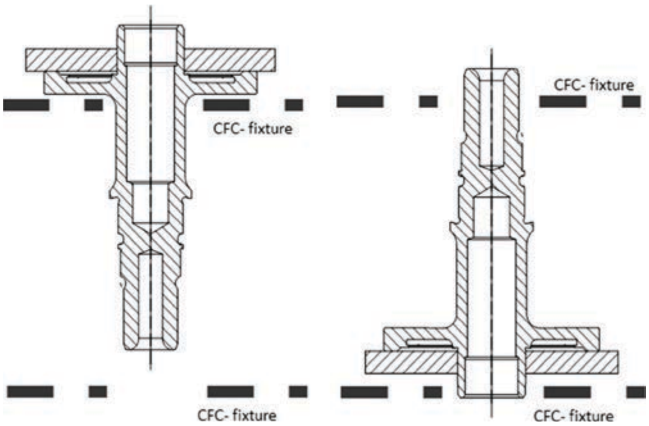

Fig. 9. Part orientation of the Input shafts during treatment: "hanging" (left) and "standing" (right)

Bild 9. Chargierung der Eingangswellen im CFC-Gestell: „hängend" (links) and „stehend" (rechts)

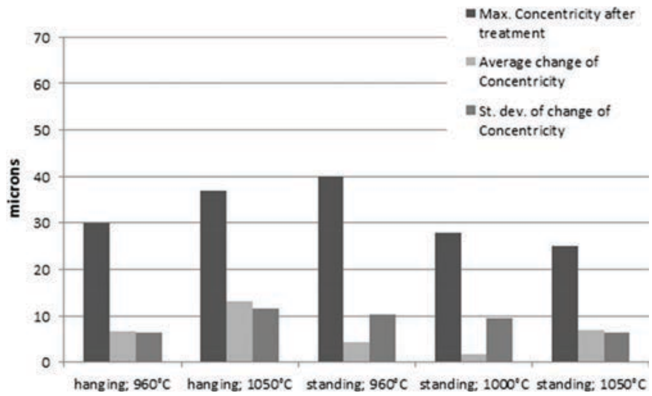

Fig. 10. Concentricity of input shafts treated in SyncroTherm with different test condition

Bild 10. Rundlauf (concentricity) der Eingangswellen nach der Einsatzhärtung in SyncroTherm für verschiedene Testbedingungen

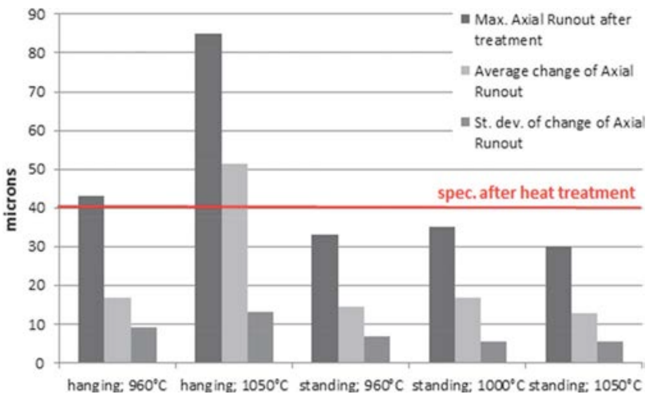

Fig. 11. Axial runout of input shafts treated in SyncroTherm under different test conditions

Bild 11. Planlauf (axial runout) der Eingangswellen nach der Einsatzhärtung in SyncroTherm für verschiedene Testbedingungen

heat treat is specified as 0.5…0.8 mm, surface hardness is specified as 690…790 HV and core hardness is specified as 340…480 HV.

Two main parameters were analysed for distortion: axial runout and concentricity. Figure 8 shows the positions for the measurements.

The carburizing temperature was varied from 960 °C to 1050 °C. Two different ways of part orientation in the CFC-fixture were tested: "hanging" and "standing", see Figure 9.

Figure 10 shows the concentricity of the shafts for different test conditions.

However for the application of these components the axial runout is more important than the concentricity. Figure 11 shows the values for maximum axial runout after treatment, the average change of axial runout and the standard deviation of the change of axial runout. Clearly the part orientation "standing" leads to much better results. When loading the shafts "standing" into the tray, the specification of axial runout after heat treatment (40 microns) was met successfully for all three analysed carb. temperatures.

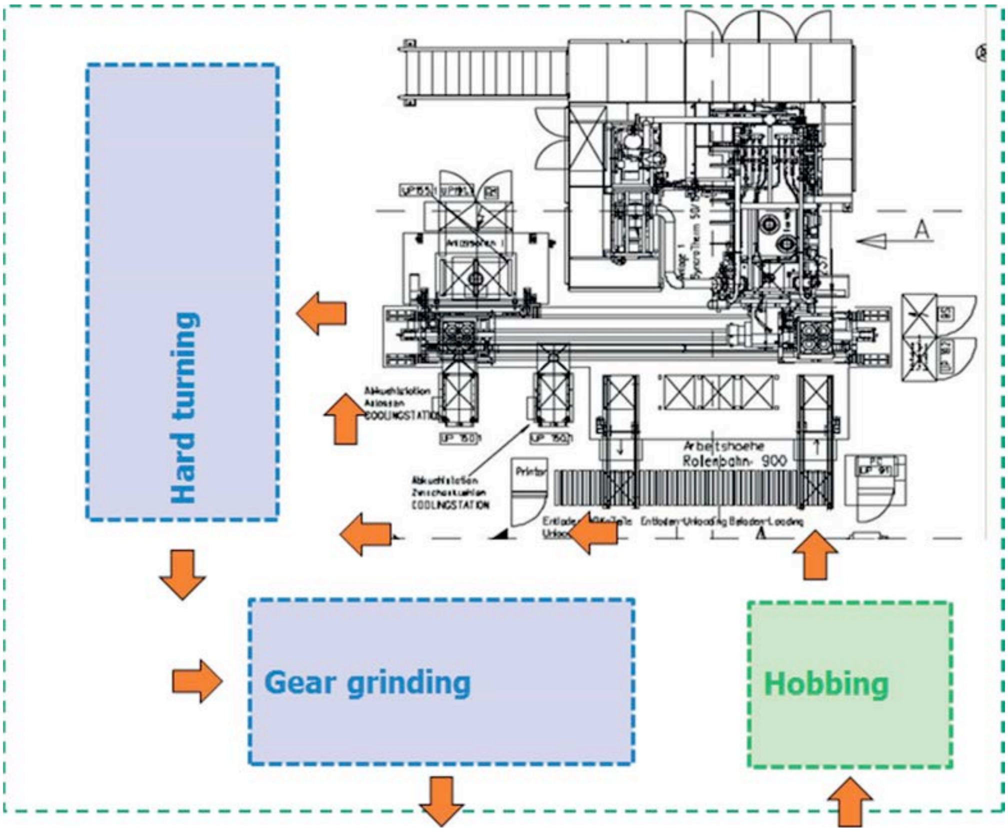

Fig. 12. Synchronized "U-shape" manufacturing cell for final drive ring gears

Bild 12. Vollständig synchronisierte Fertigungszelle in "U-Form" für die Produktion von Achsantriebsrädern

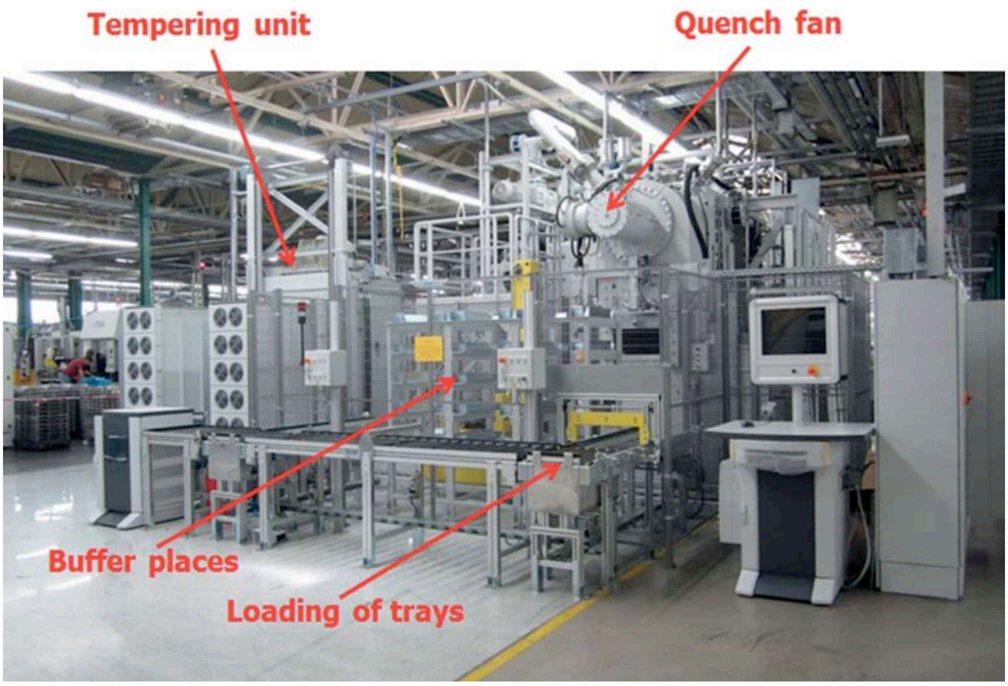

Fig. 13. SyncroTherm®-heat treat system for single-layer treatment

Bild 13. SyncroTherm®-System für die vollständig synchronisierte Wärmebehandlung

5 Synchronized vacuum heat treatment

As described before, the synchronized heat treatment provides the opportunity to integrate the case hardening process into a fully automated manufacturing line. Such a manufacturing line in "U-shape" is illustrated in Figure 12. This line consists of several modular production segments. The "green" blanks enter the system from the bottom right. The first operation is the green machining unit (hobbing) followed by the synchronized heat treat unit and then the hard machining units (hard turning and grinding). The finished gear components leave the system on the bottom left and are ready for assembly. Figure 13 shows the SyncroTherm-system applied for serial production.

The advantages of a synchronized manufacturing line regarding logistics, throughput times, space requirements, and costs have been described earlier [14].

6 Summary

Proper control of heat treat distortion is of key importance to reduce production costs in gear manufacturing. The technology of low pressure carburizing (LPC) combined with high pressure gas quenching (HPGQ) offers the potential to reduce the amount of distortion compared to conventional case-hardening technologies. The amount of distortion can be further reduced when switching from multiple layer LPC-treatment to single layer LPC-treatment ("One Piece Flow").

This was demonstrated in a comparative study on a reaction internal gear from a six speed automatic transmission. The standard deviation of Helix angle variation Vbf after heat treatment was reduced by 30 % for the left flank and by 45 % for the right flank when switching from multiple-layer to single-layer LPC-treatment for identical carburizing temperature of 900 °C. When carburizing with single-layer treatment at 1050 °C, no increase in Vbf was observed.

In addition a distortion study with single layer treatment on Input shafts was presented.

The single-layer treatment offers the possibility to manufacture gear components following the "One piece flow-philosophy". So it is possible to fully integrate heat treatment into the manufacturing line and to synchronize heat treatment with gear machining. This total integration of heat treatment into the manufacturing line allows for significant savings in logistical efforts, efforts for documentation and quality assurance. Additionally, with the fully integrated line, the turnaround time of a typical gear wheel can be drastically reduced from a few days down to less than four hours.

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